

# Polymeric metal complex catalyzed enantioselective epoxidation of olefins

Pradeep K. Dhal<sup>a,\*</sup>, Binod B. De<sup>b</sup>, Swaminathan Sivaram<sup>b</sup>

<sup>a</sup> *GelTex Pharmaceuticals Inc., 153 Second Avenue, Waltham, MA 02451, USA*

<sup>b</sup> *National Chemical Laboratory, Polymer Chemistry Division, Pune 411 008, India*

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## Abstract

Spectacular achievements in catalytic asymmetric epoxidation of olefins using chiral Mn(III)-salen complexes have stimulated a great deal of interest in designing polymeric analogs of these complexes and their use as recyclable chiral catalysts. Several strategies have been devised to anchor these chiral catalytic moieties to polymer supports. Techniques of copolymerization of appropriate functional monomers and chemical modification of preformed functional polymers have been utilized to prepare these polymers. Both organic and inorganic polymers have been used as the carriers to immobilize these metal complexes. Results of these investigations are reviewed in this article. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Asymmetric catalysis; Polymeric; Epoxidation; Olefins; Supported reagents

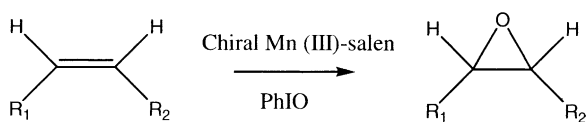
## 1. Introduction

The design and development of catalytic enantioselective organic reactions is considered as one of the most attractive and challenging frontiers in synthetic organic chemistry. The ability to produce desired organic compounds in enantiomerically pure forms from simple and readily available precursors by using small amounts of chiral catalysts has tremendous practical implications [1,2]. Among various asymmetric syntheses developed, enantioselective oxidation of unfunctionalized olefins to optically active epoxides has been considered as a powerful strategy to prepare chiral building blocks for the synthesis of biologically and pharmaceutically important compounds [3,4]. A number of strategies for asymmetric epoxidation of olefins have been developed in recent years. Among them, the mono-oxygenase model compounds based

on chiral metalloporphyrin and several other chiral metal complexes are most effective [5–8]. By using manganese complexes of chiral Schiff base ligands (Mn(III)-salen complexes) as catalysts and a mono-oxygen source (e.g. iodosylbenzene, aqueous sodium hypochlorite, etc.) as the oxidant, Jacobsen and co-workers, as well as Katsuki and co-workers have independently reported asymmetric epoxidation of unfunctionalized olefins with high enantiomeric excess (see Scheme 1) [9,10]. Facile syntheses of salen ligands from a number of readily available chiral diamines have been central to the success of this endeavor. In a short time span, it has become possible to screen a large number of ligand types to optimize the catalyst structure. On the other hand, more elaborate synthetic steps involved in chiral porphyrin synthesis limits their wide spread utility as catalytic systems.

Application of polymer-supported catalysis in organic transformations has been receiving extraordinary attention in recent years [11,12]. Immobilization

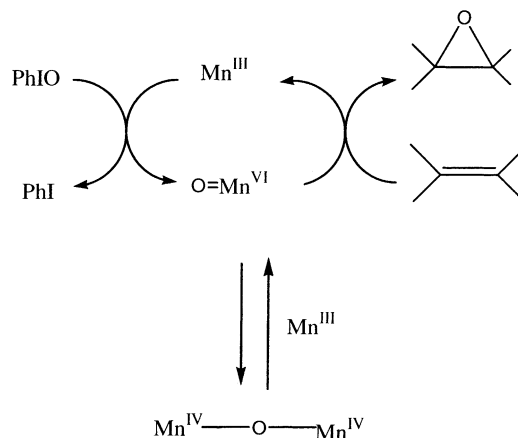
\* Corresponding author.



Scheme 1.

of homogeneous catalysts to polymeric carriers offers several practical benefits of heterogeneous catalysis, while retaining the advantages of homogeneous catalytic reactions [13,14]. Some of the attractive features of polymer-supported catalysis include: (1) easy separation of the catalysts from the reagents and reaction products; (2) simplification of methods to recycle expensive catalysts; (3) nonvolatility and non-toxic characteristics imparted to the metal complexes upon anchoring to high molecular weight polymer backbones; (4) minimization of certain catalyst deactivation pathways by site isolation. These attractive features of polymeric catalysts could possibly help in developing high throughput discovery applications as well as in developing continuous catalytic processes for industrial scale syntheses.

While use of polymeric catalysts for general organic syntheses has been known for a while, development synthetically useful polymer bound chiral catalysts for enantioselective organic transformation has been more challenging [15,16]. Development of recyclable polymeric chiral catalysts would be an important development for potential application of such important organic transformations in industrial settings. In the case of asymmetric catalytic epoxidation of unfunctionalized olefins, design and synthesis of appropriate polymeric chiral catalysts will be an important step to expand the scope of this versatile asymmetric synthesis including large-scale preparation. The polymer bound catalyst would be a cost effective alternative to this novel catalyst. One of the drawbacks of this homogeneous catalyst system is the formation of  $\mu$ -oxo-Mn(IV) dimer intermediate (Scheme 2), a catalytically deactivating species [17]. Formation of this undesired product becomes inevitable in homogeneous system, thus, limiting the possibility of catalyst recycling. By anchoring the catalytic species to a polymer carrier in appropriate concentration could lead to their mutual separation, thereby reducing the possibility of dimerization. This phenomenon of site isolation in polymer supported organic chemistry has



Scheme 2.

been utilized to carry out certain organic reactions that are not possible in solution phase homogeneous organic synthesis [18].

Shortly after the seminal discovery of the chiral Mn(III)-salen catalyzed asymmetric epoxidation of olefins, number of attempts have been made to design polymer versions of these metal complexes and their catalytic activities have been evaluated. Different approaches have been adopted to prepare polymeric chiral metal complexes. Both soluble and insoluble organic polymer resins, as well as inorganic polymers have been used as support materials. Aforementioned metal complexes have been immobilized onto polymeric carriers by covalent and electrostatic interactions. Furthermore, physical entrapment of catalysts inside support matrices has been attempted to prepare the desired immobilized catalysts. Some of the earlier articles have briefly reviewed certain aspects of the research in this area [19]. This review highlights the state-of-the-art of research in this area of polymer supported asymmetric catalysis.

## 2. Organic polymer supports

Two different approaches have been adopted to covalently attach chiral Mn(III)-salen complexes to polymer supports: (1) synthesis of appropriate functional monomers and their (co)polymerization to catalytically active polymers; and (2) attachment of metal complexes to preformed functional polymer

supports by chemical modification reactions. Following these approaches, both soluble and crosslinked chiral polymeric Mn(III)-salen complexes have been prepared and their catalytic activities during asymmetric epoxidation of olefins have been evaluated.

### 2.1. Crosslinked polymeric chiral Mn(III)-salen complexes by polymerization of functional monomers

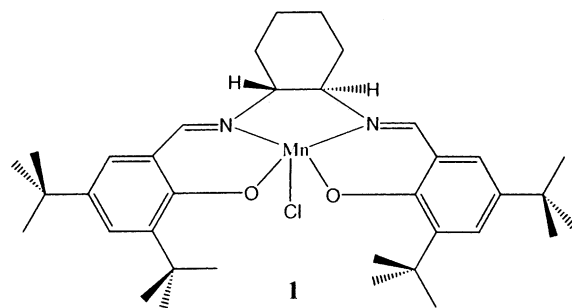
The first example of using polymeric chiral Mn(III)-salen complex as asymmetric epoxidation catalyst prepared by polymerization method was reported by our group [20,21]. As a part of our continuing study on optically active polymers and polymer supported organic synthesis [22,23], we examined the possibility of preparing polymeric catalysts for asymmetric olefin epoxidation. Our approach involved rational design of functional vinyl monomers bearing chiral Mn(III)-salen cores, whose structures are analogous to Jacobsen's catalyst **1**. Appropriate steric features as well as the C<sub>2</sub>-symmetry of **1** were incorporated into these functional monomers. Two different functional monomers containing Mn(III)-salen groups (**2** and **3**) were synthesized. These monomers were copolymerized with ethyleneglycol dimethacrylate to obtain crosslinked, macroporous polymer networks (**4** and **5**). This polymerization method enabled us to obtain rigid polymer matrices with high accessibility of the catalytic sites towards the substrates. The polymers were characterized by various analytical techniques including scanning electron microscopy. Epoxidation of different unfunctionalized olefins was carried out in the presence of these two polymers using iodosylbenzene(PhIO) as the oxidant. Results of some of the representative epoxidation reactions are summarized in Table 1. Examination of the data reveals that in terms of conversion to epoxides (i.e. chemoselectivity), both the polymeric catalysts showed activities comparable to their low molecular weight counterparts. The enantioselectivity of epoxidation was found to be sensitive to polymer structures. The polymer **5**, which was obtained from the monomer **3** containing desired bulky *tert*-butyl groups of **1**, showed better enantioselectivity than the polymer **4**. The latter polymer lacks these bulky substituents. This suggests that the steric properties of polymer networks are not adequate to impart desired chiral environment for asymmetric induction. However, in terms of

Table 1  
Asymmetric epoxidation of olefins<sup>a</sup> using polymeric catalysts **4** and **5**

Entry	Polymeric catalyst	Olefin	Yield	ee (%)
1	<b>4</b>	Styrene	76	<1
2	<b>4</b>	<i>Trans</i> -stilbene	60	<2
3	<b>4</b>	Dihydronaphthalene	72	8
4	<b>4</b>	Indene	65	28
5	<b>5</b>	<i>Trans</i> -stilbene	55	9
6	<b>5</b>	Dihydronaphthalene	70	28
7	<b>5</b>	Indene	60	25

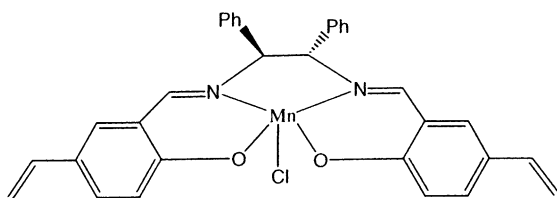
<sup>a</sup> Reactions were run at 25°C in 10 ml of acetonitrile containing 0.058 mmol eq. of catalyst, 1.92 mmol of olefin, and 3.84 mmol of iodosylbenzene.

enantioselectivity, neither of polymeric metal complexes was found to be a better catalyst. While in the homogeneous system up to 95% ee was achieved, in the best situation only 28% ee was achieved using these first generation polymeric catalysts.

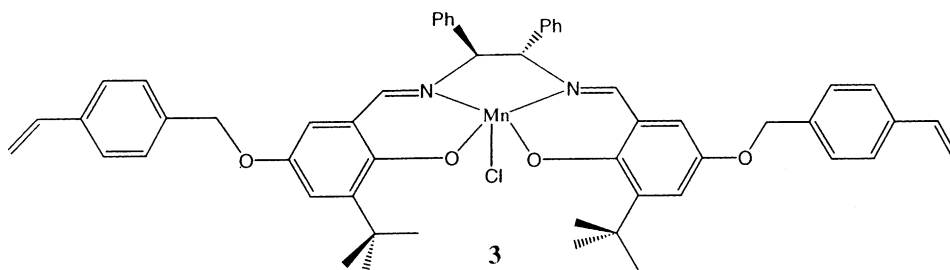


One of the problems of homogeneous catalysis using Mn(III)-salen complexes is the formation catalytically inactive  $\mu$ -oxomanganese species that limits recycling of the catalyst (vide supra, Scheme 2). One of the potential advantages of polymer bound catalysts is the possibility of suppressing this side reaction due to the spatial separation of individual metal complexes on the solid support. The recyclability of these polymeric metal complexes as catalysts for epoxidation was assessed by using the polymer **5**. The polymer was used several times without any appreciable loss in its chemo- and enantioselective activity.

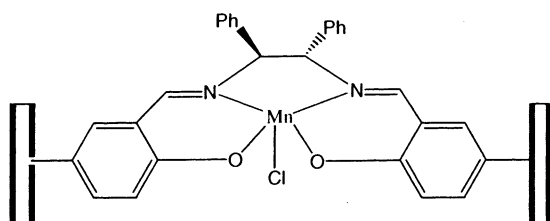
An analogous approach to synthesize polymeric chiral Mn(III)-salen complexes as catalysts for asymmetric epoxidation of olefins was developed by Salvadori and co-workers [24,25]. They synthesized



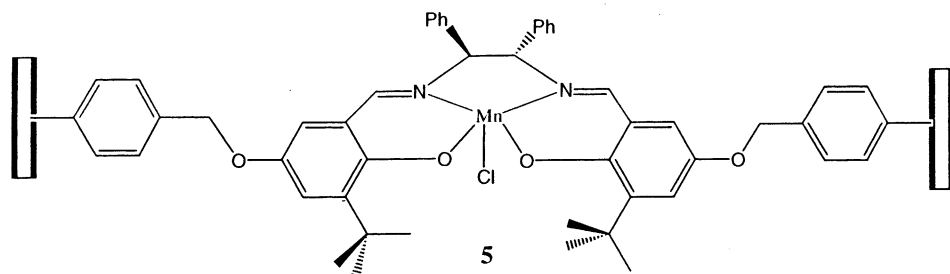
2



3



4



5

two different vinyl monomers (**6** and **7**) bearing chiral Mn(III)-salen complexes. In the case of monomer **6**, the Mn(III)-salen moiety is directly linked to polymerizable groups. On the other hand, the Mn(III)-salen moiety and polymerizable groups in monomer **7** are separated through a spacer arm. The objective of using a spacer arm has been to minimize steric hindrances

caused by the polymer backbone for the approaching olefin substrates to catalytic sites. This would lead to enhanced reaction rate and enantioselectivity. These monomers were copolymerized with divinylbenzene and styrene to obtain crosslinked metal-complexed polymers **8** and **9**. Polymer catalyzed asymmetric epoxidation of different olefins were carried

out using  $\mu$ -chloroperbenzoic acid ( $\mu$ -CPBA) and *N*-methylmorpholine-*N*-oxide (NMO) as the oxidant source. Results on some of the representative examples of epoxidation reactions are summarized in Table 2. Like the previous case, chemical yields of these polymer-catalyzed reactions are comparable to the homogeneous system. However, enantioselectivities of epoxidation using these polymeric catalysts were lower than the corresponding homogeneous systems. Introduction of a spacer arm between the polymer backbone and the Mn(III)-salen group has indeed led

to a modest improvement in enantioselectivity (see Table 2, entries 2–7). From this observation, it appears that microenvironments around the metal complexes in the polymer matrices may possibly influence the stereochemical outcome of the addition of oxygen across the double bond. Similar to earlier polymers, these two polymers were also able to retain their catalytic activities up to several cycles. These findings may enable one to design catalytically more efficient polymeric chiral Mn(III)-salen complexes by considering spacer arm and bulky substituents around salen moieties.

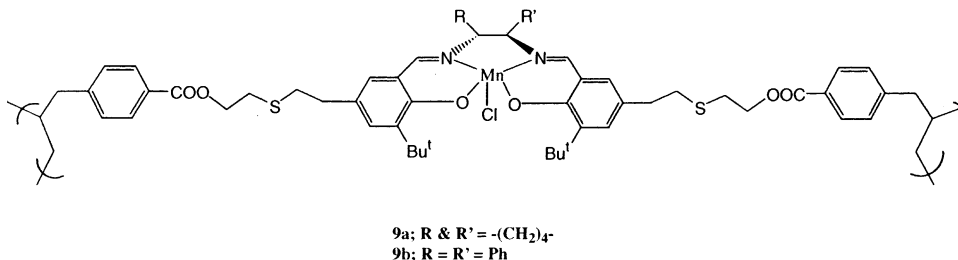
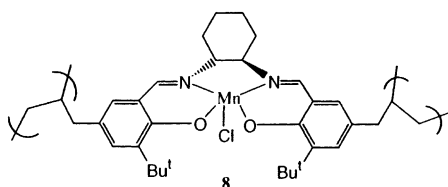
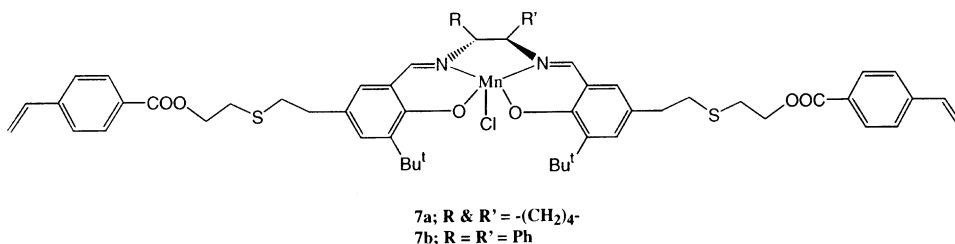
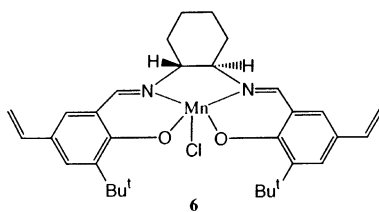


Table 2  
Asymmetric epoxidation of olefins using polymeric catalysts **8** and **9** using  $\mu$ -CPBA/NMO as oxidant<sup>a</sup>

Entry	Polymeric catalyst	Olefin	Yield	ee (%)
1	<b>8</b>	Styrene	96	14
2	<b>8</b>	$\beta$ -Methyl styrene	78	41
3	<b>9</b>	$\beta$ -Methyl styrene	92	62
4	<b>8</b>	Indene	97	27
5	<b>9</b>	Indene	96	60
6	<b>8</b>	Dihydronaphthalene	48	10
7	<b>9</b>	Dihydronaphthalene	40	21

<sup>a</sup> For experimental details, see [24,25].

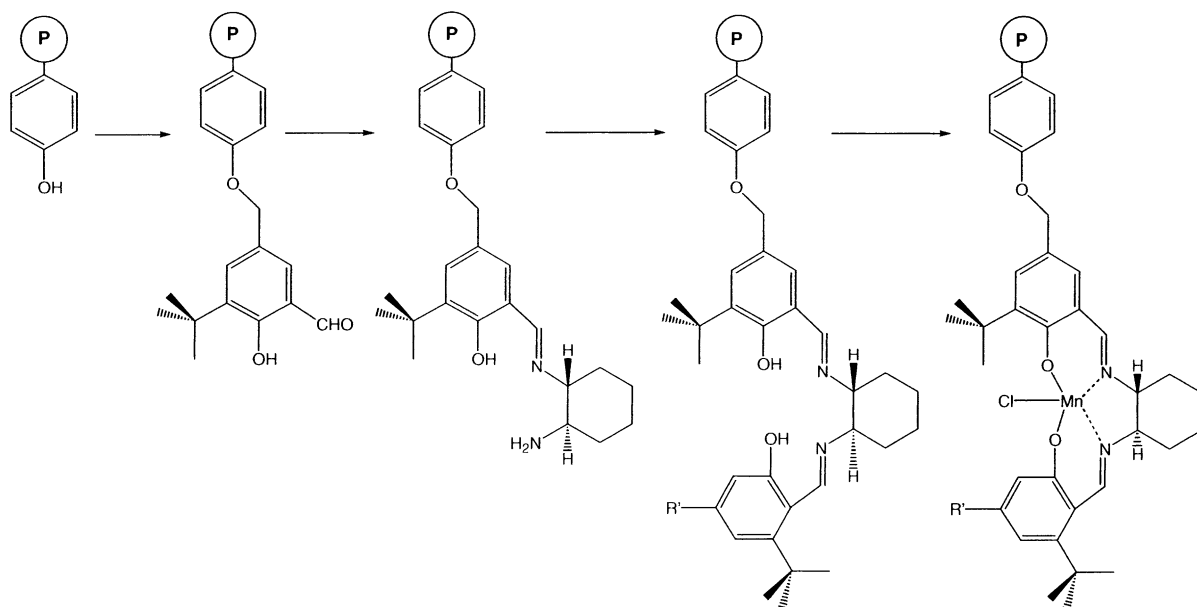
## 2.2. Crosslinked polymeric chiral Mn(III)-salen complexes by chemical modification

Chemical modification of reactive polymers offers an alternative route to prepare polymeric reagents and catalysts [26]. This methodology was adopted by several research groups to prepare polymeric chiral Mn(III)-salen complexes as catalysts for asymmetric epoxidation.

The first attempt to prepare chiral polymeric metal complexes by the chemical modification route was made by Sherrington and co-workers [27–29]. Low

enantioselectivities observed during asymmetric epoxidation using the first generation polymeric catalysts (**4**, **5**, **8** and **9**) were attributed to the structural rigidity around the catalytic center. Since metal-complexed monomers are bifunctional, they become part of crosslinking sites. This would lead to reduced mobility of polymer chains and, hence, limit the diffusion of substrates to the catalyst sites. In order to overcome this shortcoming, Sherrington and co-workers adopted chemical modification procedures to build chiral Mn(III)-salen complex moieties on polymer supports. Metal complexes were attached to polymer supports through a single point linkage in these polymers.

The synthetic strategy adopted by Sherrington and co-workers to prepare polymeric chiral Mn(III)-salen complexes is shown in Scheme 3. By using both styrene and methacrylate-based reactive polymer supports, they synthesized a set of metal-complexed polymers. Both gel type and macroporous polymer matrices were utilized for this purpose. These polymers contain Mn(III)-salen moieties located at varying distances from the polymer backbone. Variation of concentrations of salicylaldehyde groups on polymer chains during the initial modification step enabled them to control the concentration of the Mn(III)-salen groups in final polymers. This helped them to control



Scheme 3.

the formation of catalytically inactive dimeric oxo-bridged Mn(IV) species. Variation of these reaction parameters led to a series of polymer structures (**10a–d**). Asymmetric epoxidation of different olefins was carried out in the presence of these polymeric catalysts using  $\mu$ -CPBA/NMO system as the oxidant source and dichloromethane as the solvent. The results on the chemical and enantiomeric yields of epoxidation reactions for some of the representative substrates are summarized in Table 3. For a given substrate, extent of enantioselectivity was profoundly influenced by the polymer structure. In general, the morphology of the polymer resin (gel type or porous) did not significantly influence the outcome of the epoxidation reaction. However, the macroporous methacrylate resin showed maximum enantioselectivity (Table 3, entry 4). Although, the enantioselectivities of these polymeric catalysts are somewhat better than the polymers obtained by copolymerization method, they are yet inferior to their low molecular weight counterparts.

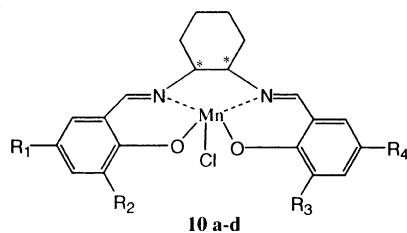
Table 3

Asymmetric epoxidation of olefins using polymeric catalysts **10a–d** using  $\mu$ -CPBA/NMO as oxidant<sup>a</sup>

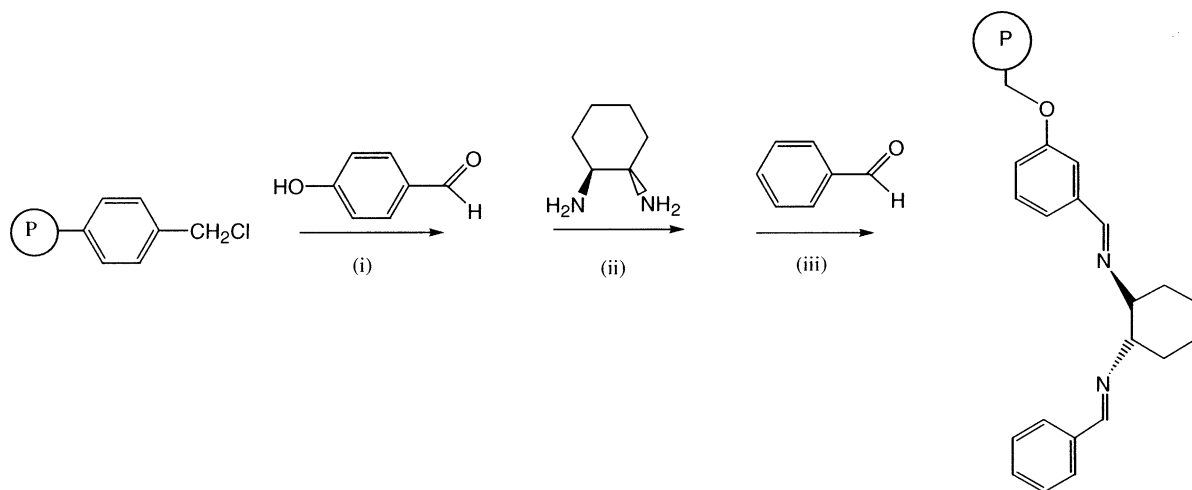
Entry	Polymeric catalyst	Olefin	Yield	ee (%)
1	<b>10a</b>	Dihydronaphthalene	61	6
2	<b>10b</b>	Dihydronaphthalene	67	16
3	<b>10b</b>	Indene	72	33
4	<b>10c</b>	1-Phenylcyclohexene	49	91
5	<b>10b</b>	1-Phenylcyclohexene	47	66

<sup>a</sup> For experimental details, see [28].

Laibinis and co-workers developed an analogous polymer modification approach to prepare polymeric chiral Mn(III)-salen complexes as asymmetric epoxidation catalysts [30,31]. Chloromethylated styrene-divinylbenzene polymer resin (Merrifield resin) was employed as the functional polymer support to incorporate metal complexes. By following a general synthetic strategy (Scheme 4), two different polymeric



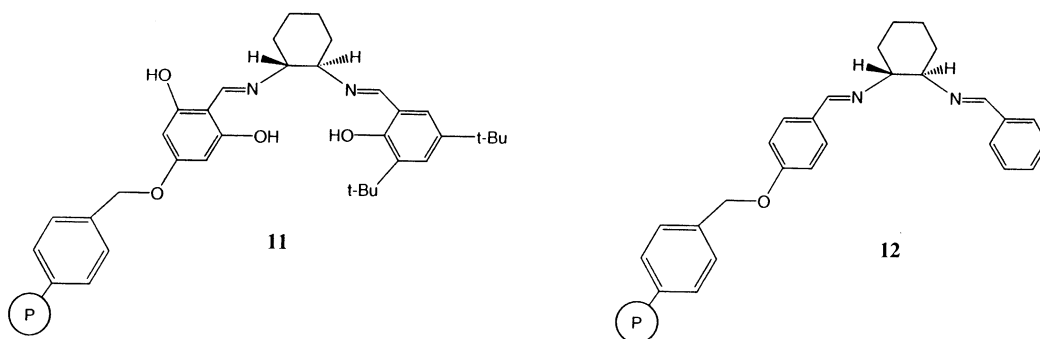
	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>	R <sub>4</sub>
<b>10a</b>	 Styrene based, gel	t-Bu-	H-	Br-
<b>10b</b>	 Styrene based, porous	t-Bu-	t-Bu-	t-Bu-
<b>10c</b>	 Methacrylate based, porous	t-Bu-		
<b>10d</b>	H-			



Scheme 4.

salen derivatives (**11** and **12**) were prepared. Subsequently, the polymeric ligands were loaded with Mn(III) ions to prepare the desired polymeric catalysts. Similar to the polymers of Sherrington and co-workers, these immobilized salen ligands are

significantly higher in dichloromethane than in acetonitrile (Table 4, entries 1 and 2). A modest enantioselectivity (46%) was observed for dihydronaphthalene as the substrate. On the other hand, an impressive enantioselectivity was achieved for *cis*- $\beta$ -methylstyrene.



linked to polymer backbone through single anchoring sites. Different steps of these polymer modification reactions were monitored by infrared spectroscopy. Asymmetric olefin epoxidation reactions were carried by using Mn(III)-**11** complex as the polymeric catalyst and sodium hypochlorite as the oxidant. The results of epoxidation reactions are summarized in Table 4. A significant effect of the solvent system on enantioselectivities of epoxide formation was observed. While, the chemical yield was not sensitive to the nature of the media, the enantioselectivity was signif-

icantly higher in dichloromethane than in acetonitrile (Table 4, entries 1 and 2). A modest enantioselectivity (46%) was observed for dihydronaphthalene as the substrate. On the other hand, an impressive enantioselectivity was achieved for *cis*- $\beta$ -methylstyrene.

In both the cases, recycling of polymeric metal complexes (for assess their ability to retain the catalytic activities) led to drop in both conversion and enantioselectivity. This is contrary to the copolymerization systems, where the catalytic activities were retained after multiple stages of catalyst recycling. Since the copolymerization approach involved use of well-defined functional monomers, their incorporation in the polymer matrices is more homogeneous. On the other hand, multistep chemical modification reactions carried out on polymer supports has the propensity



Table 4

Asymmetric epoxidation of olefins using polymeric catalyst Mn(III)-**12** and NaOCl as the oxidant<sup>a</sup>

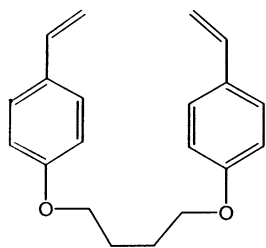
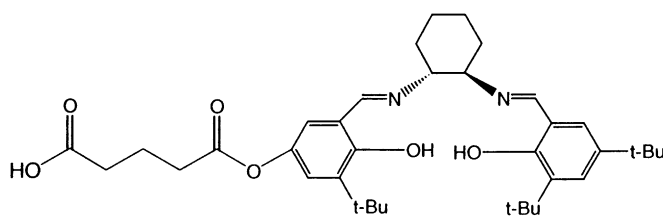
Entry	Solvent	Olefin	Yield (%)	ee (%)
1	Acetonitrile	Dihydronaphthalene	56	7
2	Dichloromethane	Dihydronaphthalene	42	46
3	Dichloromethane	<i>Cis</i> - $\beta$ -methylstyrene	2/27 <sup>b</sup>	79/12 <sup>c</sup>
4	Dichloromethane	Styrene	7	9

<sup>a</sup> For experimental details, see [30].<sup>b</sup> Reported yields are for *cis/trans*-epoxides, respectively.<sup>c</sup> The ee's refer to *cis/trans*-enantiomers.

to incorporate structural inhomogeneity to the polymer backbone including the presence of Mn(III)-salen species close enough to produce undesired dimeric  $\mu$ -oxo-Mn(IV) species. Unfortunately, there has been no direct analytical method to identify and quantify the presence of these dimeric Mn(IV) species in the polymers. Furthermore, Laibinis and co-workers had observed the leakage of catalytically active species from polymer supports due to cleavage of the linkage between the polymer backbone and ligands.

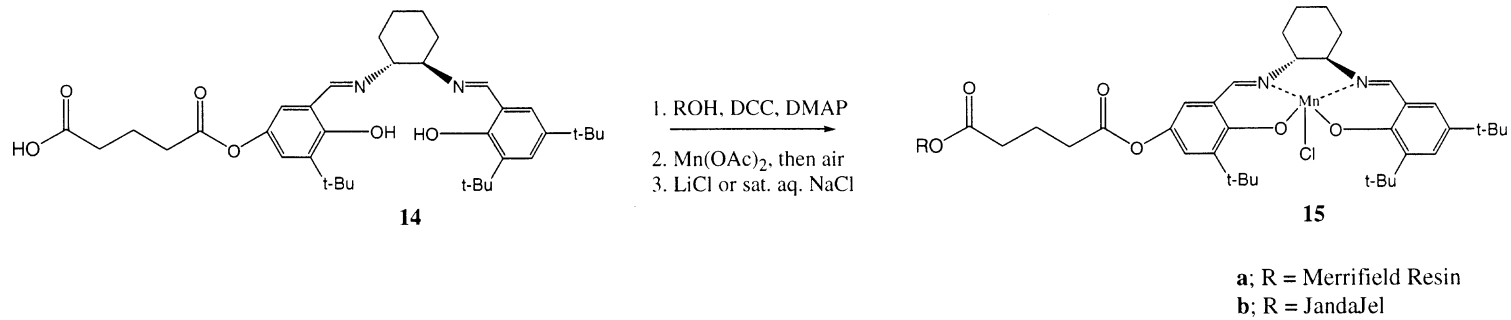
A polymeric chiral Mn(III)-salen complex prepared by chemical modification approach exhibiting improved enantioselective catalytic activity has recently been reported by Reger and Janda [32]. Both Merrified resin and JandaJel (a hydroxy-benzyl functional resin prepared by using a novel crosslinker **13**) were used as the functional polymer supports to anchor the salen derivatives to the polymer backbone. A chiral salen derivative with a glutamate spacer (**14**) was used as the appropriate metal complexing ligand. Coupling

of these polymeric catalysts by using  $\mu$ -CPBA as the oxidant and NMO as an additive. The results of the reactions are summarized in Table 5. These polymeric catalysts showed by far the most impressive chemo- and enantioselectivity. Highest enantioselectivity was achieved in the case of  $\beta$ -methyl styrene as the substrate ( $\sim 88\%$  ee), which is comparable to the corresponding homogeneous system. In order to ascertain the role of the catalyst concentration in the polymer resin (which would have the consequence on the formation of catalytically inactive oxo-bridged Mn(IV) dimer), they synthesized polymeric supports containing varying amounts of Mn(III)-salen complex (0.10–0.75 mmol/g). Epoxidation reactions were carried out in the presence of these polymeric metal complexes by using  $\beta$ -methyl styrene as the substrate. Interestingly, all polymers brought about nearly similar enantioselectivities. Furthermore, these catalysts could be recycled up to three times without any apparent loss of their activities.

**13****14**

of this compound to polymer supports through an ester linkage (Scheme 5) and subsequent metallation of the resulting polymeric ligand produced the desired polymeric chiral catalyst **15**. Asymmetric epoxidation of different olefins were carried out in the presence

The method adopted by Janda and co-workers to prepare chiral polymeric Mn(III)-salen complexes is principally distinct from the approaches of by the earlier two approaches in the following manner. While the present approach involves attaching



Scheme 5.

Table 5  
Asymmetric epoxidation of olefins using polymeric catalysts **15a** and **b** using  $\mu$ -CPBA/NMO as the oxidant<sup>a</sup>

Entry	Catalyst	Olefin	Yield (%)	ee (%)
1	<b>15a</b>	Styrene	61	35
2	<b>15a</b>	Dihydronaphthalene	69	78
3	<b>15a</b>	<i>Cis</i> - $\beta$ -methylstyrene	75	86
4	<b>15b</b>	Styrene	81	51
5	<b>15a</b>	Dihydronaphthalene	71	79
3	<b>15a</b>	<i>Cis</i> - $\beta$ -methylstyrene	77	88

<sup>a</sup> For experimental details, see [32].

well-defined salen ligands to polymer carriers in a single step, earlier studies involved multistep syntheses on polymeric supports to prepare immobilized metal complexes. Multistep chemical reactions on insoluble polymers have the potential to bring about structural heterogeneity. This means during each modification step incomplete reactions could produce polymer-linked undesired species. These side products can not be removed by traditional purification procedures employed in organic synthesis. Contamination of the polymer support with these unknown and undesired species might be the reason for poor enantioselectivities exhibited by earlier polymers. It appears from these studies that physicochemical properties of polymer supports including solvent swellability and accessibility of catalytic sites are key to their success as solid phase asymmetric epoxidation catalysts.

### 2.3. Soluble polymeric chiral Mn(III)-salen complexes

In general, majority of polymer-supported organic transformations has been carried out using insoluble polymer resins as carrier matrices. Although insoluble polymers possess desired features (such as easy separation of the products from the catalysts or unused reagents from the products) as support materials, some times these heterogeneous reaction conditions impose certain complications while transferring solution-phase methodologies to solid-phase reactions [33,34]. Some of the shortcomings of insoluble polymer-supported catalysts/reagents include inaccessibility of catalytic sites, non-linear reaction kinetics, compositional heterogeneities of polymeric catalysts/reagents, etc. In order to achieve more solution

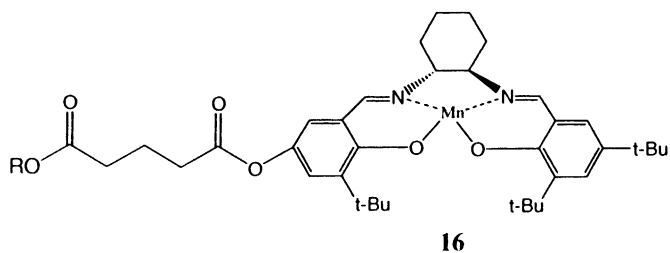
like conditions using polymeric supports, attempts have been made to develop soluble polymer bound reagents/catalysts [35,36]. Selective precipitation of a soluble polymeric catalyst/reagent from the reaction mixture after completion of the reaction has been utilized to isolate the product. Selective precipitation of polymers from the reaction mixtures can be accomplished either by employing appropriate solvents or by taking advantage of the lower critical solution temperature (LCST) property of certain polymers. The latter characteristic enables one to precipitate the polymer from the solution by heating the reaction mixture to a temperature above the LCST of the polymer [37]. Polymers like poly(ethylene glycol) (PEG), end functionalized polyethylene, soluble polystyrene and copolymers of *N*-isopropyl acrylamide have been utilized for this purpose.

In order to achieve better enantioselectivity, Janda and co-workers set out to prepare PEG-based soluble polymeric chiral Mn(III)-salen complexes. They used monomethoxy-PEG and poly(styrene-co-4-hydroxymethyl styrene) as the polymeric carrier for this purpose [32]. Esterification reaction between these functional polymers and the ligand **14** and subsequent metallation of polymeric ligand offered polymeric catalysts **16a** and **b**. Polymer catalyzed asymmetric epoxidation of different olefins was carried out using  $\mu$ -CPBA as the oxidant and the results of these reactions are summarized in Table 6. Enantioselectivities and chemical yields are quite comparable to the analogous heterogeneous system (vide supra, see Table 5). Recovery of these soluble polymeric catalysts was accomplished by precipitation of the reaction mixture from ether or THF. Both the polymeric catalysts could be reused up to three times without losing their chemo- and enantioselective catalytic activities.

Table 6  
Asymmetric epoxidation of olefins using polymeric catalysts **16a** and **16b** using  $\mu$ -CPBA/NMO as the oxidant<sup>a</sup>

Entry	Catalyst	Olefin	Yield (%)	ee (%)
1	<b>16a</b>	Styrene	82	52
2	<b>16a</b>	Dihydronaphthalene	70	76
3	<b>16a</b>	<i>Cis</i> - $\beta$ -methylstyrene	79	88
4	<b>16b</b>	Styrene	76	51
5	<b>15b</b>	Dihydronaphthalene	69	73
3	<b>15b</b>	<i>Cis</i> - $\beta$ -methylstyrene	79	90

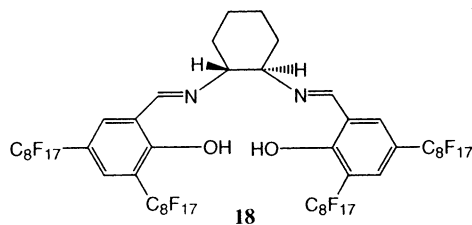
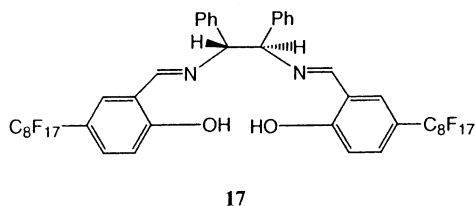
<sup>a</sup> For experimental details, see [32].



**a;** R = MeO-PEG<sub>5000</sub>

**b;** R = non-crosslinked poly(styrene-co-hydroxymethyl styrene)

Another interesting approach to prepare soluble, phase separable immobilized chiral Mn(III)-salen complexes has been reported by Pozzi et al. [38]. This approach is based on the new technique of Fluorous Biphasic System (FBS). In FBS technique, ligands/reagents are attached to a perfluorocarbon chain. The perfluorocarbon tail renders these species to be insoluble in conventional reaction media; thus, behaving like a polymer immobilized catalyst [39,40]. The catalyst can be separated from the reaction mixture by phase separation techniques. Pozzi et al. synthesized two different perfluorinated ligands **17** and **18** with the core metal complex structure resembling the well-known Jacobsen catalyst **1**. Epoxidation of olefins in the presence of these metal complexes by using NaOCl or H<sub>2</sub>O<sub>2</sub> as oxidant gave poor enantioselectivity. On the other hand, by using molecular oxygen/pivalaldehyde oxidant system of Mukaiyama and co-workers [41], very high enantioselectivity (~90% ee) was achieved with indene as the substrate.



### 3. Inorganic supports

Desirable physical characteristics exhibited by inorganic polymer supports (viz. silica gels, zeolites, etc.) have been the drive forces to explore these materials as the carriers to prepare solid phase catalysts

and reagents [42,43]. Some of these characteristics include superior mechanical and thermal properties, well-defined pore sizes and compatibility to a wide range of solvents. Several attempts have been made to immobilize chiral salen-based metal complexes to these inorganic supports and the use of resulting functional supports as catalysts for asymmetric epoxidation of olefins. Immobilization of chiral metal complexes to these inorganic matrices has been carried out by gel entrapment, covalent linkage as well as by electrostatic interactions.

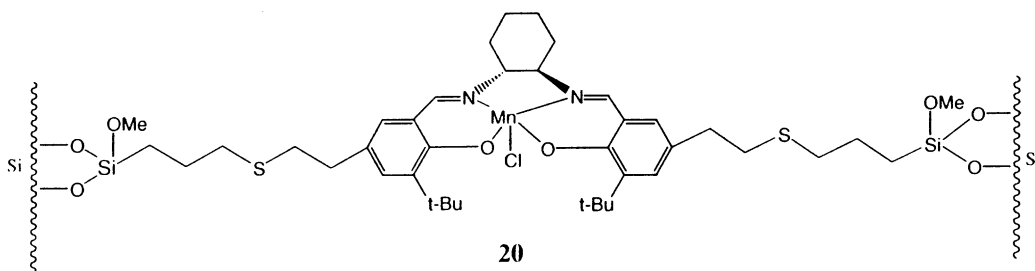
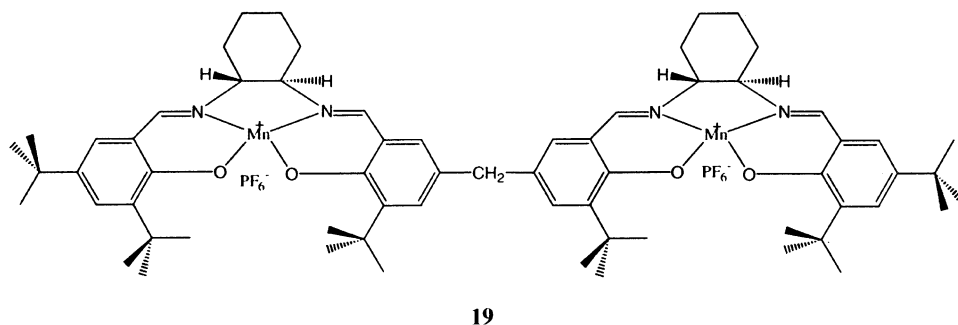
#### 3.1. Matrix entrapment

Physical entrapment of low molecular weight chiral Mn(III)-salen complexes inside polydimethylsiloxane (PDMS) membranes was reported by Vankelecom and co-workers [44,45]. Their first attempt involved

the immobilization of the well-known Jacobsen type Mn(III)-salen complex **1**. Subsequently, they synthesized a novel dimeric Mn(III)-salen complex **19** and immobilized this metal complex within PDMS membrane. Although immobilized by simple entrapment inside an elastomeric membrane, leaching out of these complexes from the PDMS matrices was

not evident during subsequent chemical operations [45]. Asymmetric epoxidation of different olefins in the presence of these two immobilized catalysts was carried out using NaOCl as the oxidant. Chemo- and enantioselective catalytic activities of these two immobilized catalysts for olefin epoxidation are comparable to the corresponding homogeneous systems. This approach appears to be a general and facile way to prepare catalytically active immobilized metal complexes. In this case, chiralities of metal complexes are retained and no supplementary chemical bonding is required. Therefore, it enables one to minimize the need for further chemical manipulations to link catalyst moieties to solid supports. By the appropriate choice of membrane thickness and crosslinking density, leaching out of metal complexes can be prevented.

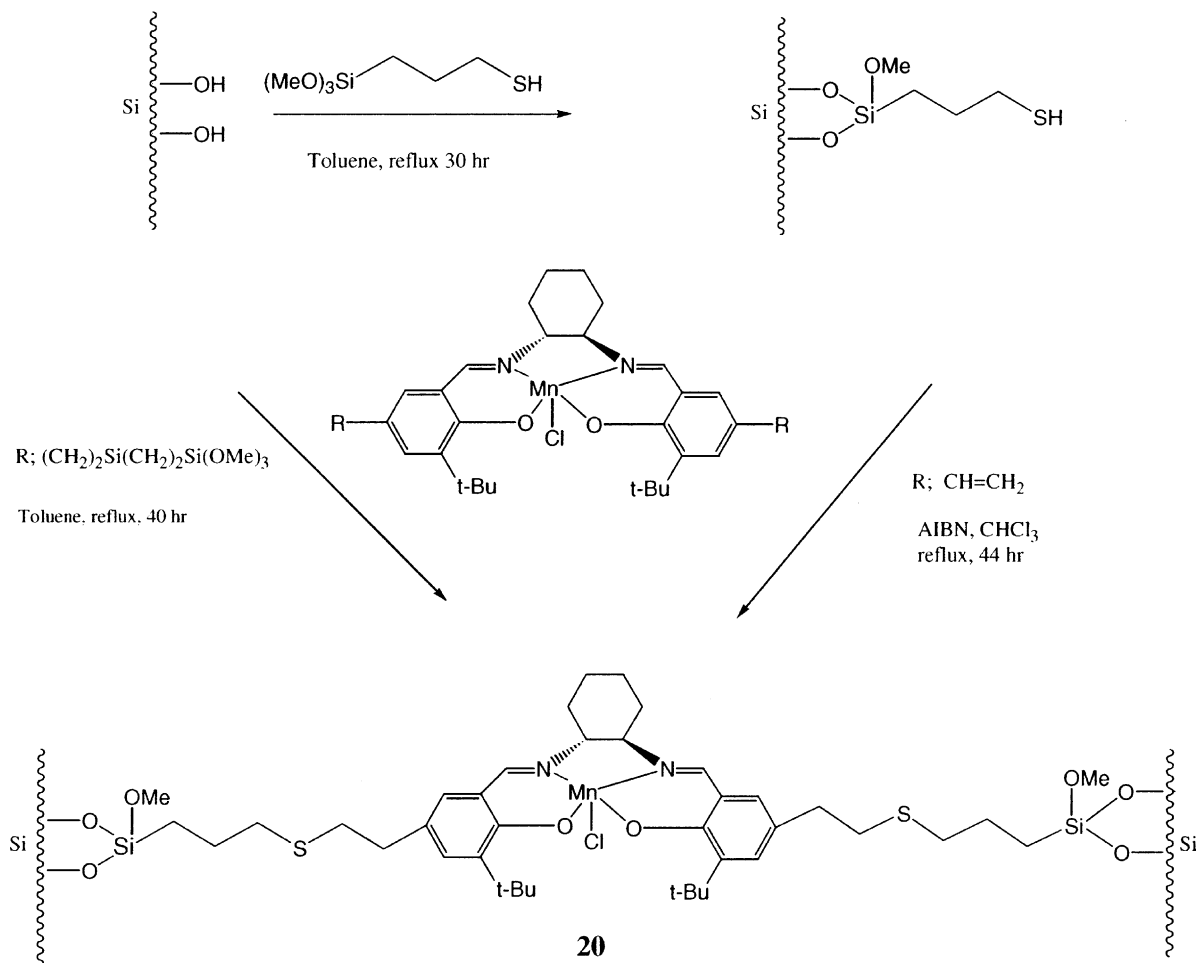
Si(100) silica gel. The resulting functional silica particles were subjected to free radical coupling with a diolefin functionalized Mn(III)-salen complex to prepare the desired immobilized metal-complex **20**. The reaction sequences employed to prepare **20** are illustrated in Scheme 6. Asymmetric epoxidation of olefins were carried out in the presence of **20** using  $\mu$ -CPBA/NMO as the oxidant source. The enantioselectivities of these reactions are modest and are compared to the earlier reported organic polymers by this group [24,25]. Similar to polymeric systems, in the present case the Mn(III)-salen moiety is connected to the silica support by two-point attachment. This would have resulted in restricted mobility of metal-complex moieties as well as unfavorable steric restriction for the olefin substrate to catalytic sites, thus, manifesting modest enantioselectivity.



### 3.2. Covalent linkage

Silica gel containing covalently linked chiral Mn(III)-salen complex was prepared by Salvadori and co-workers [46]. Thiol functionalized silica particles were prepared by condensing  $\gamma$ -mercaptopropyltrimethoxy silane to commercially available LiChrospher

Anchoring of chiral Mn(III)-salen complex to inorganic supports through single site linkage was carried out by Kim and Shin [47]. This approach is analogous to the step-by-step coupling procedures employed by Sherrington and co-workers in the case of organic polymers. In the present case, siliceous MCM-41 has been used as the base inorganic support,

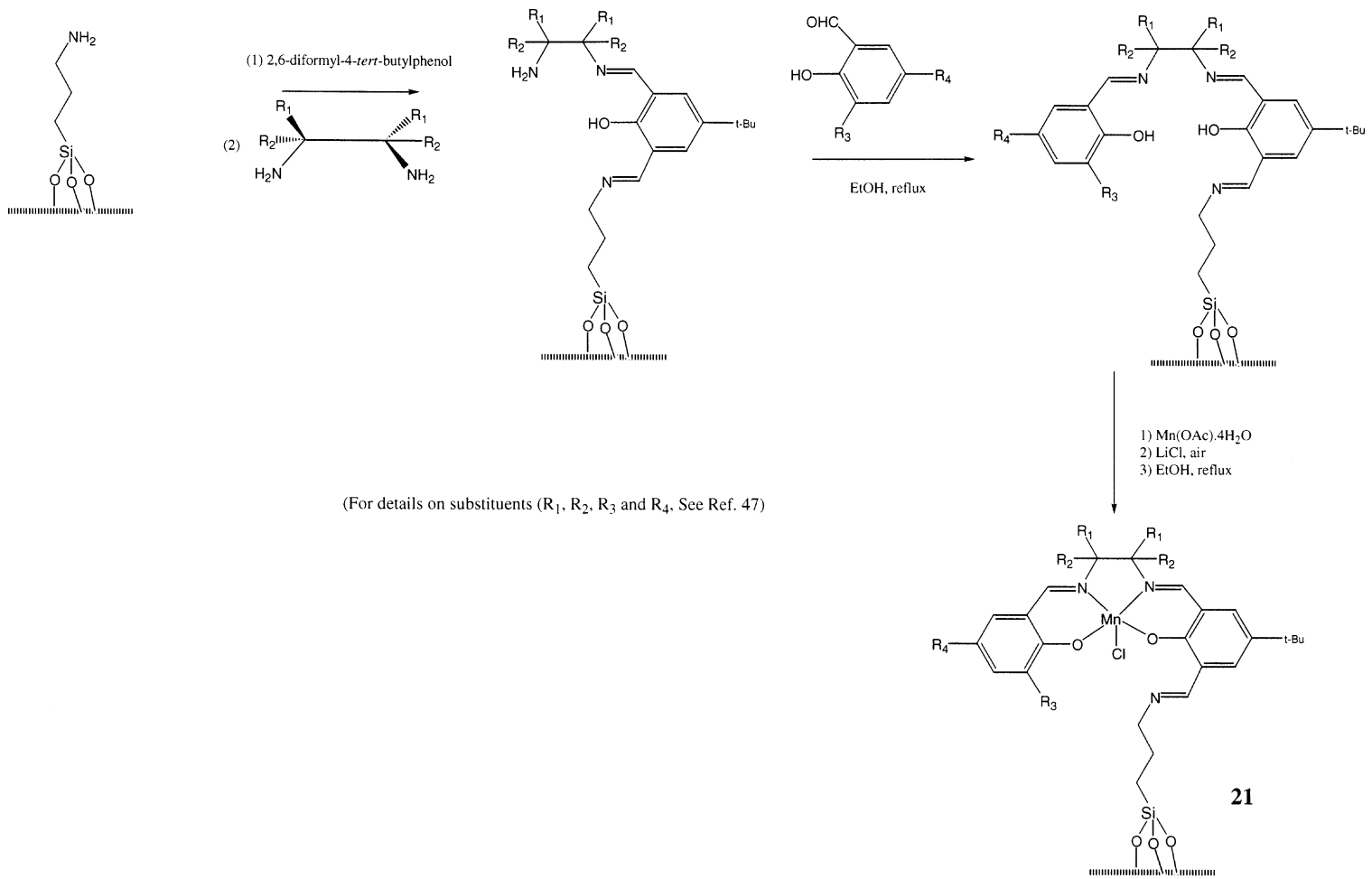


Scheme 6.

which was transformed to an amino functional support by the reaction with three-aminopropyltrimethoxy silane. Step-by-step coupling reactions were carried out on this amino functional solid support (Scheme 7) produced the desired immobilized catalyst **21**. Asymmetric epoxidation of olefins catalyzed by this catalyst was carried out using  $\mu$ -CPBA/NMO as the oxidant system. With styrene and  $\alpha$ -methyl styrene as the substrates, high chemical and enantiomeric yields ( $\sim 70\%$ ) were achieved. Reactions were carried out at both 0 and  $-78^\circ\text{C}$ , but there was no influence of temperature on enantioselectivity.

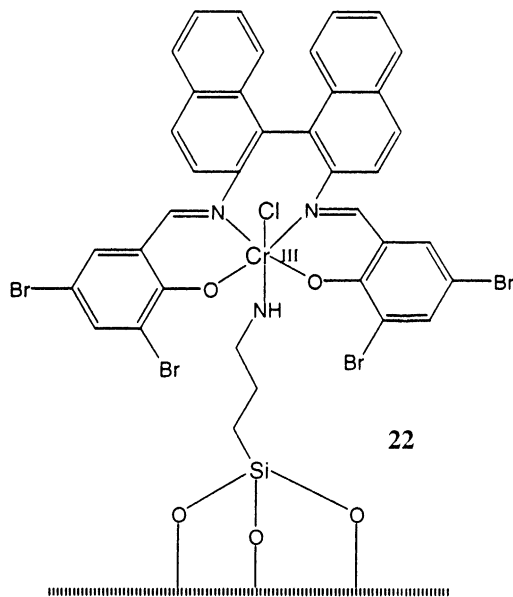
### 3.3. Electrostatic interaction

By using aminopropyl silyl modified zeolite (MCM-41) as the inorganic carrier, Zhou et al. [48] prepared a supported chiral Cr(III)-salen complex, **22**. In addition to replacing the usual metal ion Mn by Cr, they used an atropisomeric diamine to prepare the chiral salen ligand. Coordination bonding between the amino group of the support and the metal center of the chiral complex was used for immobilization purpose. Catalytic activity of this supported metal complex for asymmetric olefin epoxidation was



Scheme 7.

investigated by using iodosylbenzene as the oxidant. Satisfactory enantioselectivity with ee values in the range of 40–77% were observed for a number of substituted styrenes as substrates.



#### 4. Conclusion and outlook

Solid-supported asymmetric catalysts for enantioselective epoxidation of olefins offer a complimentary alternative to the homogenous catalysis of this important organic transformation. Concerted efforts by a number of research groups over the past 5 years has enabled us to formulate the design criteria to develop polymeric chiral Mn(III)-salen complexes, which not only exhibit catalytic activities comparable to the homogeneous system, but also enables us to reuse the catalyst up to several cycles. The concepts and reaction schemes designed by different groups to develop catalytically efficient polymeric metal complexes represent a new dimension in molecular catalysis and can be applicable to other reactions. Thus, besides being scientifically exciting, these enterprises can be utilized for developing practically useful catalysts for an industrially important reaction. Synthetic methodologies employed to generate these polymeric metal complexes offer the general scheme to incorporate different metal ions to a given polymeric ligand. This

principle would enable us to generate combinatorial catalyst libraries for several transition metal catalyzed asymmetric organic transformations. This review illustrates the synergistic interplay of organic synthesis, polymer chemistry and molecular catalysis that will continue to provide the challenges and tools for continuing research in the frontier of selective catalysis in organic synthesis.

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